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Indirect Violation of CP, T and CPT in the B_d-system [1]

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Abstract

The problem of indirect violation of discrete symmeties CP, T and CPT in a neutral meson system can be described using two complex parameters ε and δ, which are invariant under rephasing of meson and quark fields. For the B_d system, where the width difference between the physical states is negligible, only $\mathrm{Re}(\delta)$ and $\mathrm{Im}(\varepsilon)$ survive. As a consequence, the traditional observables constructed for kaons, which are based on flavour tag, are not useful for the analogous study in this system. We describe how using a CP tag and studying *CP-to-flavour* transitions of the B mesons, we may build asymmetries, alternative to those used for the kaon, which enable us to test T and CPT invariances of the effective hamiltonian for the B_d system.

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Indirect Violation of CP, T and CPT in the B_d-system

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The problem of indirect violation of discrete symmeties CP, T and CPT in a neutral meson system can be described using two complex parameters ε and δ, which are invariant under rephasing of meson and quark fields. For the B_d system, where the width difference between the physical states is negligible, only Re(δ) and Im(ε) survive. As a consequence, the traditional observables constructed for kaons, which are based on flavour tag, are not useful for the analogous study in this system. We describe how using a CP tag and studying *CP-to-flavour* transitions of the B mesons, we may build asymmetries, alternative to those used for the kaon, which enable us to test T and CPT invariances of the effective hamiltonian for the B_d system.

1. Introduction

The time evolution of a neutral meson system is governed by an effective hamiltonian [1]. The problem of indirect violation of discrete symmetries refers to the non-invariance of this hamiltonian under the corresponding operations.

For the kaon system, this study has been performed by the CP-LEAR experiment [2] from the preparation of definite flavour states K^0-$\bar{K}^0$. These tagged mesons evolve in time and their later decay to a semileptonic final state projects them again on a definite flavour state. The study of this *flavour-to-flavour* evolution allows the construction of observables which violate CP and T, or CP and CPT.

Contrary to what happens in the kaon case, for the B_d-system the width difference $\Delta\Gamma$ between the physical states is expected to be negligible. In this system the T- and CPT-odd observables proposed for kaons, which are based on flavour tag, vanish. but, making use of CP tag, the B_d entangled states can be used to construct alternative observables which are sensitive to T and CPT independently of the value of $\Delta\Gamma$ [3].

2. The parameters

In the neutral B-meson system the physical states are a linear combination of B^0 and $\bar{B}^0$. If they are written in terms of CP eigenstates, one has to introduce two complex parameters, $\varepsilon_{1,2}$, to describe the CP mixing.

$$|B_{\substack{1\\2}}\rangle = \frac{1}{\sqrt{1+|\varepsilon_{\substack{1\\2}}|^2}}\left[|B_\pm\rangle + \varepsilon_{\substack{1\\2}}|B_\mp\rangle\right] , \qquad (1)$$

where $|B_\pm\rangle \equiv \frac{1}{\sqrt{2}}(I \pm CP)|B^0\rangle$. Then $\varepsilon_{1,2}$ are invariant under rephasing of the meson states, and physical when the CP operator is well defined [4].

Alternatively, one may use the parameters $\varepsilon \equiv (\varepsilon_1+\varepsilon_2)/2$ and $\delta \equiv \varepsilon_1 - \varepsilon_2$, whose interpretation in terms of symmetries is simpler.

Discrete symmetries impose different restrictions on the effective mass matrix, $H = M - \frac{i}{2}\Gamma$: CPT invariance requires $H_{11} = H_{22}$, T invariance imposes $\mathrm{Im}(M_{12}\mathrm{CP}^*_{12}) = \mathrm{Im}(\Gamma_{12}\mathrm{CP}^*_{12}) = 0$, and CP conservation requires both conditions to be simultaneously satisfied. Furthermore, in the exact limit $\Delta\Gamma = 0$, customary for the B_d-system, both Re(ε) and Im(δ) vanish. Therefore we have four real parameters which carry information on the symmetries of the effective mass matrix

- Re(ε) $\Rightarrow$ CP and T violation, with $\Delta\Gamma \neq 0$;
- Im(ε) $\Rightarrow$ CP and T violation;
- Re(δ) $\Rightarrow$ CP and CPT violation;
- Im(δ) $\Rightarrow$ CP and CPT violation, $\Delta\Gamma \neq 0$.

3. The entangled state: CP tag

In a B factory operating at the $\Upsilon(4S)$ peak, correlated pairs of neutral B-mesons are produced through $e^+e^- \to \Upsilon(4S) \to B\bar{B}$. The special features of this system can be used to study CP [5] and CPT [6] violation in B mesons.

In the CM frame, the resulting B-mesons travel in opposite directions, each one evolving with the effective hamiltonian. The $B\bar{B}$ state has definite $L = 1$, $C = -$ and $\mathcal{P} = -$, being $\mathcal{P}$ the operator which permutes the spatial coordinates, so that the initial state may be written as

$$|i>= \frac{1}{\sqrt{2}}\left(|B^0, \overline{B}^0 > -|\overline{B}^0, B^0 >\right) \tag{2}$$

The correlation between both sides of the entangled state holds at any time after the production. As a consequence, one can never simultaneously have two identical mesons at both sides of the detector. This permits the performance of a flavour tag: if at $t = 0$ one of the mesons decays through a channel, such as a semileptonic one, which is only allowed for one flavour of the neutral B, the other meson in the pair must have the opposite flavour at $t = 0$.

The entangled $B-\bar{B}$ state can also be expressed in terms of the CP eigenstates $|B_\pm\rangle$ as

$$|i>= \frac{1}{\sqrt{2}}\left(|B_-, B_+ > -|B_+, B_- >\right) \tag{3}$$

Thus it is also possible to carry out a CP tag, once we have a CP-conserving decay into a definite CP final state, so that its detection allows us to identify the decaying meson as a B_+ or a B_-.

In Ref. [7] we described how this determination is possible and unambiguous to $\mathcal{O}(\lambda^3)$, which is sufficient to discuss both CP-conserving and CP-violating amplitudes in the effective hamiltonian for B_d mesons. Here λ is the flavour-mixing parameter of the CKM matrix [8]. The determination is based on the requirement of CP conservation, to $\mathcal{O}(\lambda^3)$, in the (sd) and (bs) sectors. To this order, however, CP-violation exists in the (bd) sector, and it can be classified by referring it to the CP-conserving direction. A B_d decay that is governed by the couplings of the (sd) or (bs) unitarity triangles, or by the $V_{cd}V_{cb}^*$ side of the (bd) triangle, will not show any CP violation to $\mathcal{O}(\lambda^3)$. We may say that such a channel is free from direct CP violation. Examples are $J/\Psi K_S$, with CP $= -$, and $J/\Psi K_L$, with CP $= +$.

To extract information on the symmetry parameters we may study the time evolution of the entangled state (2) and its decay into a final configuration (X, Y). In our notation, X is the decay product observed on one side of the detector at a certain time, and Y the product detected on the opposite side after a Δt.

We will only consider here decay channels X, Y which are either flavour or CP conserving. Then the final configuration (X, Y) corresponds to a certain transition at the mesonic level, i.e. the B state tagged by the X decay evolves for a period Δt and is then projected into a flavour or CP eigenstate by means of the Y decay.

4. The asymmetries

By comparing the probabilities corresponding to different processes we build time-dependent asymmetries that allow the extraction of the relevant parameters. The observables can be classified into three types.

4.1. Flavour-to-flavour genuine asymmetries

If one detects semileptonic decays on both sides of the detector, then the transition at the meson level is of the kind *flavour-to-flavour*. The mesonic transitions for such a final configuration appear in Table 1, where $\ell^\pm$ represents the final decay product of a semiinclusive decay $B \to \ell^\pm X^\mp$. From these processes we can construct two non-trivial asymmetries, which are the analogous, in the B-system, to the traditional observables used for kaons. The first two processes in Table 1 are conjugated under CP and also under

Table 1
Flavour-to-flavour transitions

(X, Y)	Transition
(ℓ^+, ℓ^+)	$\bar{B}^0 \to B^0$
(ℓ^-, ℓ^-)	$B^0 \to \bar{B}^0$
(ℓ^+, ℓ^-)	$\bar{B}^0 \to \bar{B}^0$
(ℓ^-, ℓ^+)	$B^0 \to B^0$

T, then we may construct a genuine asymmetry by comparing the corresponding intensities

$$A(\ell^+,\,\ell^+) \approx \tfrac{\mathrm{Re}(\varepsilon)}{1+|\varepsilon|^2}. \qquad (4)$$

On the other hand, the last two processes in Table 1 are related by a CP or a CPT transformation. Therefore, the corresponding asymmetry,

$$\begin{aligned} A(\ell^+,\,\ell^-) &\approx -2\left[\mathrm{Ch}\tfrac{\Delta\Gamma\Delta t}{2} + \cos(\Delta m \Delta t)\right]^{-1} \\ &\left[\mathrm{Re}\left(\tfrac{\delta}{1-\varepsilon^2}\right)\mathrm{Sh}\tfrac{\Delta\Gamma\Delta t}{2} - \mathrm{Im}\left(\tfrac{\delta}{1-\varepsilon^2}\right)\sin(\Delta m \Delta t)\right], \end{aligned} \qquad (5)$$

is also a genuine CP and CPT observable.

In both cases, the resulting asymmetry vanishes unless $\Delta\Gamma \neq 0$. Thus measuring a small value for these observables does not impose a straightforward bound on the size of symmetry violation, because the vanishingly small $\Delta\Gamma$ of B-mesons would hide any symmetry breaking effect.

4.2. CP-to-flavour genuine asymmetries

We may construct alternative asymmetries making use of the CP eigenstates, which can be identified in this system by means of a CP tag. If the first decay product, X, is a CP eigenstate produced along the CP-conserving direction, and Y is a semileptonic channel, then the mesonic transition corresponding to the configuration $(X,\,Y)$ is of the type *CP-to-flavour*. The order of appearance of both final states matters, because for the reverted configuration, $(Y,\,X)$, we have a *flavour-to-CP* transition. In Table 2 we show the mesonic transitions, with their related final configurations, connected by genuine symmetry transformations to $B_+ \to B^0$, i.e. $(J/\Psi K_S,\,\ell^+)$. Comparing the intensity of $(J/\Psi K_S,\,\ell^+)$ with each of them we construct three genuine asymmetries. Next, we show the results to linear order in δ and in the limit $\Delta\Gamma = 0$.

Table 2
Transitions connected to $(J/\Psi K_S,\,\ell^+)$.

$(X,\,Y)$	Transition	Transformation
$(J/\Psi K_S,\,\ell^-)$	$B_+ \to \bar{B}^0$	CP
$(\ell^-,\,J/\Psi K_L)$	$B^0 \to B_+$	T
$(\ell^+,\,J/\Psi K_L)$	$\bar{B}^0 \to B_+$	CPT

$$\begin{aligned} A_{\mathrm{CP}} &= -2\tfrac{\mathrm{Im}(\varepsilon)}{1+|\varepsilon|^2}\sin(\Delta m \Delta t) \\ &\quad + \tfrac{1-|\varepsilon|^2}{1+|\varepsilon|^2}\tfrac{2\mathrm{Re}(\delta)}{1+|\varepsilon|^2}\sin^2\left(\tfrac{\Delta m \Delta t}{2}\right), \end{aligned} \qquad (6)$$

is the CP odd asymmetry, which has contributions from T-violating and CPT-violating terms. The first term, odd in Δt, is governed by the T-violating $\mathrm{Im}(\varepsilon)$, whereas the second term, Δt even, is sensitive to CPT violation through the parameter $\mathrm{Re}(\delta)$.

$$\begin{aligned} A_{\mathrm{T}} &= -2\tfrac{\mathrm{Im}(\varepsilon)}{1+|\varepsilon|^2}\sin(\Delta m \Delta t) \\ &\quad \left[1 - \tfrac{1-|\varepsilon|^2}{1+|\varepsilon|^2}\tfrac{2\mathrm{Re}(\delta)}{1+|\varepsilon|^2}\sin^2\left(\tfrac{\Delta m \Delta t}{2}\right)\right], \end{aligned} \qquad (7)$$

the T asymmetry, needs $\varepsilon \neq 0$, and includes CPT even and odd terms. Moreover, in the limit we are considering, turns out to be purely odd in Δt.

$$A_{\mathrm{CPT}} = \tfrac{1-|\varepsilon|^2}{1+|\varepsilon|^2}\tfrac{2\mathrm{Re}(\delta)}{1+|\varepsilon|^2}\frac{\sin^2\left(\frac{\Delta m \Delta t}{2}\right)}{1-2\frac{\mathrm{Im}(\varepsilon)}{1+|\varepsilon|^2}\sin(\Delta m \Delta t)}, \qquad (8)$$

is the CPT asymmetry. It needs $\delta \neq 0$, and includes both even and odd time dependences, so that there is no definite symmetry under a change of sign of Δt.

Measuring the presented asymmetries (6)-(8) with good time resolution, so to separate even and odd Δt dependences, should be enough to determine the parameters $\frac{2\mathrm{Im}(\varepsilon)}{1+|\varepsilon|^2}$ and $\frac{1-|\varepsilon|^2}{1+|\varepsilon|^2}\frac{2\mathrm{Re}(\delta)}{1+|\varepsilon|^2}$, which govern CP, T violation and CP, CPT violation, respectively, in the B_d mixing.

Contrary to what happened in the case of flavour tag, the CPT and T asymmetries based on a CP tag do not vanish due to the smallness of $\Delta\Gamma$. Instead, they provide a set of observables which could separate the parameters δ and ε.

4.3. CP-to-flavour non-genuine asymmetries

The asymmetries defined in the previous paragraphs are genuine observables, since each of them compares the original process with its conjugated under a certain symmetry and is thus odd under the corresponding transformation. Nevertheless the measurement of all those quantities requires to tag both B_+ and B_- states. The last needs, from the experimental point of view, a good reconstruction of the decay $B \to J/\Psi K_L$, not so easy to achieve as for the corresponding $J/\Psi K_S$ channel.

But it is also possible to construct useful asymmetries from final configurations (X, Y) with only $J/\Psi K_S$. In Table 3 we show the different transitions we may study from such final states. From the comparison between $(J/\Psi K_S,\, \ell^+)$ and each process in the table we can construct three asymmetries. The first one will correspond to the genuine CP asymmetry $A(J/\Psi K_S,\, \ell^-) = A_{\rm CP}$. We find that, in the exact limit $\Delta\Gamma = 0$, Δt and T operations become equivalent, so that $A(\ell^+,\, J/\Psi K_S) \equiv A_{\rm T}$ and $A(\ell^-,\, J/\Psi K_S) \equiv A_{\rm CPT}$. But these asymmetries are not genuine. They do not correspond to true T- and CPT-odd observables, for the processes we are comparing are not related by a symmetry transformation. This implies that the presence of $\Delta\Gamma \neq 0$ may induce non-vanishing values for them, even if there is no true T or CPT violation. But even if that is the case, it is possible to separate out the different parameters, if good enough Δt is provided [9].

Table 3
Final configurations with only $J/\Psi K_S$.

(X, Y)	Transition	Transformation
$(J/\Psi K_S,\, \ell^-)$	$B_+ \to B^0$	CP
$(\ell^+,\, J/\Psi K_S)$	$\bar{B}^0 \to B_-$	Δt
$(\ell^-,\, J/\Psi K_S)$	$\bar{B}^0 \to B_-$	Δt+CP

5. Conclusions

We present an overview of the possibilities to explore indirect violation of CP, T and CPT in a neutral meson system from the quantities that B-factories can measure. The asymmetries analyzed here exploit their time dependences in order to separate out two different ingredients: on one hand CP and T violation, described by ε, and on the other CP and CPT violation, given by δ. Such a study is possible, even if $\Delta\Gamma = 0$, if one goes beyond *flavour-to-flavour* transitions and makes use of CP tags.

We classify the observables into three different types:

- Genuine asymmetries for T or CPT violation, based on *flavour-to-flavour* transitions at the meson level, which need $\Delta\Gamma \neq 0$.
- Genuine observables, based on the combination of flavour and CP tags, which do not need $\Delta\Gamma$.
- Making use of the equivalence between Δt and T reversal operations for $\Delta\Gamma = 0$, we have also considered non genuine observables, involving only the hadronic decay $J/\Psi K_S$.

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REFERENCES

1. P. K. Kabir, The CP Puzzle, *Academic Press* (1968), p. 99
2. A. Apostolakis et al., *Phys. Lett.* **B456** (1999) 297.
3. M. C. Bañuls and J. Bernabéu, *Phys. Lett.* **B464** (1999) 117.
4. M. C. Bañuls and J. Bernabéu, *Phys. Lett.* **B423** (1998) 151.
5. L. Wolfenstein, *Nucl. Phys* **B246** (1984) 45; M. B. Gavela et al., *Phys. Lett.* **B162** (1985) 197; Z. Xing, *Phys. Rev.* **D53** (1996) 204.
6. M. Kobayashi and A. I. Sanda, *Phys. Rev. Lett.* **69** (1992) 3139; Z. Xing, *Phys. Rev.* **D50** (1994) 2957; V. A. Kostelecký and R. Van Kooten, *Phys. Rev.* **D54** (1996) 5585; P. Colangello and G. Corcella, *Eur. Phys. J.* **C1** (1998) 515.
7. M. C. Bañuls and J. Bernabéu, JHEP 9906 (1999) 032.
8. M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49** (1973) 652; L. Wolfenstein, *Phys. Rev. Lett.* **51** (1983) 1945.
9. M. C. Bañuls and J. Bernabéu, hep-ph/0005323